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Determine and study the pathogens, insects, and other factors causing the epidemic decline of Ohia and Koa forests in Hawaii

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A FINAL REPORT FOR

FOREST SERVICE, PSW GRANT No. 3

Determine and Study the Pathogens, Insects, and Other Factors Causing the Epidemic Decline of Ohia and Koa Forests in Hawaii

WORK UNIT: PSW 1205

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A. TITLE: DETERMINE AND STUDY THE PATHOGENSM INSECTSM AND OTHER FACTORS CAUSING THE EPIDEMIC DECLINE OF OHIA AND KOA FORESTS IN HAWAII.

B. GRANT: FOREST SERVICE, PSW GRANT NO. 3 (PL 85-934 [42 USC 1881-1893])

C. OBJECTIVES:

1. The role of pathogenic organisms in the decline of ohia and koa.

2. Degree of association of insects with pathogens or diseased condition of trees.

3. The role of edaphic or climatological factors which may: (a) cause or predispose the trees to disease or insects, and (b) influence the intensity and/or rate of spread of the disease or insects.

D. RESULTS: (as related to the Objectives)

1. The role of pathogenic organisms in the decline of ohia and koa. In these studies three fungi were demonstrated to be pathogenic to ohia (Metrosideros collina subsp. polymorpha) and koa (Acacia koa), i.e., Phytophthora cinnamomi, Pythium vexans and Calonectria crotalariae (Cylindrocladium sp.). Of the three, P. cinnamomi was the most pathogenic and widespread in the decline areas and so was selected as the most likely pathogen candidate for more detailed studies. Phytophthora cinnamomi caused rootlet necrosis ofohia and was recovered from 96% of the decline areas as well as 24% of healthy areas sampled from a total of 130 locations on the Island of Hawaii. The population of this fungus was determined to be about the same in soil of the decline forest as in that of the apparently healthy forest. It was isolated from roots of 20 endemic, 2 indigenous, and 6 introduced plant species of 22 different plant families found in Hawaiian tropical rain forests. All isolates tested were of the A^2 mating type. A technique was developed whereby concentrated zoospores could be determined by a microsyringe method without prior termination of spore motility. This method of concentration was applicable also to other types of fungal propagules. The population determined with this method had smaller standard deviation than those determined by the hemacytometer method. Applications of the fungicides, Dexon^R, Difolitan^R, and Benlate^R in addition to a complete fertilizer to declining ohia trees resulted in a better response than applications of a complete fertilizer only. However, declining ohia trees did not respond to treatment with fungicides alone.

Pythium vexans was found to cause rootlet necrosis of ohia. It was recovered from 3 out of 5 areas in healthy forests and 6 out of 38 areas in declining forests. It was less pathogenic to ohia rootlets than P. cinnamomi.

Calonectria crotalariae was found to be pathogenic to both ohia and koa seedlings, however, it is not widespread. A medium

for enumeration and isolation from soil of C. crotalariae. Among the three propagule types of C. crotalariae, microsclerotia were the most infective to ohia seedlings, while the infection potential of conidia and ascospores was about the same. The ability of these three propagule types to colonize organic matter did not differ significantly. Microsclerotia, but not conidia or ascospores of C. crotalariae remained viable after 3 years in soil.

Armillaria mellea, a root-rotting fungus was originally suspected of playing a major role in the decline of the ohia forests. However, it has been determined that although A. mellea is relatively widespread and serious in isolated areas, it could not be considered a major factor in the epidemic ohia decline. Fourteen new hosts, in Hawaiian forests, were found for A. mellea.

Plant parasitic nematodes were found associated with ohia. Helicotylenchus, Criconemoides, and Xiphimema sp. were most commonly found, however, not in concentrations which could be considered to be contributing to the decline of ohia. However, root-knot nematodes (Meloidogyne incognita) were found abundant in the roots of koa which were showing symptoms of decline. The occurrence of root-knot nematodes in koa forests is widespread.

2. Degree of association of insects with pathogens or diseased condition of trees.

Psyllid insects (Trioza spp.) causing cone, pit and stem galls are abundant on ohia and their damage is often severe. In an effort to determine the role of these insects on decline ohia-psyllid spray plots were established to determine the efficacy of systemic insecticides on these pests. Trees treated with foliar applications of dimethoate (Cygon^{R}) at intervals of approximately 5 weeks have remained virtually free of psyllid infestation. This treatment of dimethoate also eliminated other sucking insects such as mealybugs and scales. Test trees were maintained free of large leaf and twig galls as well as leaf pit galls and non-gall forming psyllid nymphs. However, as the psyllid life cycle from egg to adult requires from two to four months, psyllid nymphs which became established on treated trees between treatments were killed at an early stage of development. Trunk application, by paint brush, of Azodrin suspended in Volck oil have less satisfactory results than dimethoate. Average mortality of psyllid nymphs in samples from Azodrin-treated trees was between 80-90%. It appears that Azodrin does not persist in the tree as long as dimethoate.

In 23 months there has been no observable differences in dimethoate and Azodrin-treated trees as compared to untreated control trees. None of either treated trees or the control trees have died, however, some deterioration (dieback of twigs

and small branches) in both treated and control trees. Dysyston failed to give satisfactory control of the insects on ohia.

Cerambycid larvae (Plagithmysus bilineatus) are numerous in declining trees. Stain is sometimes associated with the galleries and the fungus, Cylindrocladium, has been found associated with frass and galleries in ohia and koa. However, no interrelationship has been established. Two Cylindrocladium spp. were inoculated to young ohia trees both as foliar twig and root inoculations. The results of these tests were apparently negative.

An association between the insect, Xylosandrus compactus, and a fungus, Fusarium sp., in a twig blight of koa was found.

3. The role of edaphic or climatological factors which may: (a) cause or predispose the trees to disease or insects, and (b) influence the intensity and/or rate of spread of the disease or insects.

Declining ohia trees showed a positive growth response to fertilization by producing numerous new leaf buds on defoliated branches and main trunks in two months. Leaf buds opened and produced vigorous, healthy new leaves. One year after the fertilizer treatment all trees in the intermediate decline group became healthy in appearance. These trees remained healthy for two and one-half years after fertilizer treatment. Declining ohia trees in more than 10 additional decline areas throughout the Island of Hawaii were tested. All trees treated with fertilizer responded in a similar way at all locations. These results indicate that ohia trees may be declining due to the low plant nutrition because the roots are debilitated by the pathogenic effects of root pathogen(s), a low soil fertility base, and/or a combination of both. Declining ohia respond positively to NPK without micronutrients and to a combination of NP. However, ohia did not respond to a mixture of micronutrients alone, or combinations of NK and PK.

Phytophthora cinnamomi was detected in soil particles carried by boots, vehicle tires, and wild pig hoofs. The fungus was dispersed as zoospores in rainsplash and runoff water from ohia forests.

The role of endotrophic mycorrhizae and ohia was studied. Some of the common Glomus spp. (Endogone) and Gigas spp. (E. gigantea) have been found associated with the roots of ohia but not in the quantity which might be indicative of a highly beneficial or obligatory nature. Ohia failed to respond positively when seedlings were inoculated with the chlamydosporic propagules of the fungus. Further, attempts to increase the propagules of the mycorrhizae by using corn (Zea Mays) as an alternative host were not successful.

E. PUBLISHED PAPERS (and summaries)

1. Laemmlen, F. F. and R. V. Bega. 1972. Decline of ohia and koa forests in Hawaii. Phytopathology 62:770 (absrt.).

Metrosideros collina and Acacia koa forests occupy ca. 600,000 acres on the Island of Hawaii. According to aerial surveys in 1954, 67,000 acres of this area were in a slight (less than 20% dead trees) to severe (60% or more dead trees) decline. In 1965, the affected areas had increased by 10,000 acres, and the severely affected portion had increased from 5,000 acres (1954) to 14,000 acres (1965). Recent serial and ground surveys indicate a steadily deteriorating situation. The forest decline is seen as a rapid wilt and death of trees and/or a slow progressive decline causing a thinning of foliage, many dead twigs, and general unthrifty appearance followed by complete defoliation and death. The most severely affected forest in on the slopes of Mauna Kea at an elevation of 750-1,700 m. The region receives 250-750 cm median annual rainfall. Possible causal and contributing agents include Armillaria mellea, Phytophthora cinnamomi, Diatrype princeps, Xylosandrus compactus, and Plagithmysus bilineatus, as well as drainage changes in the substratum, wild pigs, and other mammals, microorganisms, and insects. Quantitative and qualitative studies of the decline have been initiated.

2. Ko, W. H., L. L. Chase, and R. K. Kunimoto. 1973. A microsyringe method for determining concentration of fungal propagules. Phytopathology 63:1206-1207.

Concentration of zoospores was determined by a microsyringe method without prior termination of spore motility. The method was applicable also to other types of fungal propagules and the population determined with this method had smaller standard deviation than the hemacytometer method.

3. Kliejunas, J. T., and W. H. Ko. 1973. Root rot of ohia (Metrosideros collina subsp. polymorpha) caused by Phytophthora cinnamomi. Plant Disease Reporter. 57:383-384.

Phytophthora cinnamomi caused root rot and death of ohia (Metrosideros collina subsp. polymorpha) in greenhouse tests. The isolation of this fungus from ohia in the field was correlated with high rainfall and poor drainage, but not with ohia decline.

4. Kliejunas, J. T., and W. H. Ko. 1973. Nutrient deficiency as an important factor in ohia decline. Second Int. Congr. Plant Pathol., Minneapolis, Minn. Sept. 5-12, 1973.

Declining ohia trees (Metrosideros collina polymorpha) were treated individually with both macro- and micro-elements by

either ground application or foliar spray at 5 different locations. Three months after treatment, 100% of the moderately declining and 88% of the severely declining trees produced numerous new buds followed by new leaf growth from these buds. The average number of new buds produced by each treated and non-treated tree was 151 and 13, respectively. Some of the treated trees produced more than 1,000 new buds and many of the moderately declining trees appeared healthy within 5 months after treatment. Ground application was more effective than foliar spray. All ohia trees within three 600 sq. ft. and a 5,000 sq. ft. plot responded in a similar way to a complete fertilizer broadcasted at a rate of 700 lbs./acre. Declining ohia trees also responded to a mixture of NPK without micro-elements. Individually, N, P, K, and a mixture of micro-elements were not effective. These results strongly suggest a deficiency of inorganic nutrients as an important factor contributing to ohia decline.

5. Kliejunas, J. T., and W. H. Ko. 1974. Deficiency of inorganic nutrients as a contributing factor to ohia decline. Phytopathology 64:891-896.

Stands of native ohia trees in Hawaii are in serious decline and many trees have died. Declining trees treated with a complete fertilizer (NPK plus micronutrients) responded by producing numerous new leaf buds on branches and trunks. The trees also responded to a mixture of NPK without micronutrients. Application of N, P, and K individually or a mixture of micro-nutrients were not effective. Declining trees responded to a combination of NP, but not to combinations of NK and PK. Results indicated that ohia trees are declining because of nutrient deficiency.

6. Kliejunas, J. T., and W. H. Ko. 1974. Role of Phytophthora cinnamomi in ohia decline. APS Annual Meeting, Vancouver, B.C., Aug. 11-15, 1974.

The presence of Phytophthora cinnamomi in healthy and declining ohia forests on the Island of Hawaii was determined by soil baiting and by direct isolation from roots. The fungus was present in most declining areas and in some healthy areas surveyed. In ohia forests, P. cinnamomi was also isolated from necrotic roots of other declining native vegetation such as Styphelia tameiameiae, Perrottetia sanwicensis and Myrsine sp. All isolates of P. cinnamomi tested belonged to A_2 mating type. Ohia seedlings grown in low fertility medium were killed by P. cinnamomi, whereas those grown in fertilized medium remained healthy. Declining ohia trees recovered and thrived in the presence of P. cinnamomi when they were treated with a complete fertilizer.

7. Laemmlen, Franklin and R. V. Bega. 1974. Hosts of Armillaria Mellea in Hawaii. Plant Dis. Reptr. 58:102-103.

Several new hosts of the root rot fungus Armillaria mellea have been found in the State of Hawaii. Most are on wildland plants. To date, no sporophores of the fungus have been found on any of the Islands. The new hosts are:

Coprosma spp.	Pinus pinea
Gouldia spp.	Pipturus albidus
Hibiscadelphus hualalaiensis	Prunus domestica
Malus sylvestris	P. persica
Myoporun sandwicense	Straussia sp.
Myrsine lessertiana	Styphelia tameiameiae
Osmanthus sandwicensis	Zanthoxylum diptalum

8. Kliejunas, J. T., and W. H. Ko. 1975. The occurrence of Pythium vexans in Hawaii and its relation to ohia decline. Plant Dis. Reptr. 59:392-395.

Pythium vexans De Bary caused root rot of ohia (Metrosideros Collina [Forst.] Gray subsp. polymorpha [Gaug.] Rock) in greenhouse and field tests. No correlation between ohia tree decline and occurrence of P. vexans in ohia tree roots or ohia forest soil was evident. Pythium vexans was recovered from ohia forests of healthy appearance but not from all decline areas. When P. vexans was present in decline areas, Phytophthora cinnamomi Rands was also present. In greenhouse tests, Phytophthora cinnamomi was a more virulent root pathogen than P. vexans.

F. PUBLICATIONS SUBMITTED FOR PUBLICATIONS (with summaries)

1. Hwang, S. C., and W. H. Ko. A medium for enumeration and isolation of Calonectria crotalariae from soil. Phytopathology (in press).

Calonectria crotalariae produced brownish colonies with visible strands of microsclerotia on acidified medium containing 2% dextrose, 0.02% peptone and 2% agar. With this medium 83 to 93% of C. crotalariae propagules were recovered from artificially inoculated soil. The population of this fungus in the vicinity of diseased papaya seedlings ranged from 350 to 3,050 propagules/g dried soil.

2. Hwang, S. C., and W. H. Ko. Biology of conidia, ascospores, and microsclerotia of Calonectria crotalariae in soil. Phytopathology (in press).

Among the three propagule types of Calonectria crotalariae, microsclerotia were most infective to papaya and ohia seedlings

while the infection potential of conidia and ascospores was about the same. Ability of these three propagule types to colonize dead papaya stems did not differ significantly. The population of conidia, ascospores, and microsclerotia decreased 87, 46, and 20%, respectively after 8-month incubation in soil. Only microsclerotia remained viable after 8 months when colonized papaya tissues containing conidia, ascospores, and microsclerotia of C. crotalariae were incubated in soil. Microsclerotia, but not conidia or ascospores were recovered from soils collected from planting holes in which papaya seedlings were killed by C. crotalariae 3 years ago in an abandoned field.

3. Kliejunas, J. T., and W. H. Ko. Association of Phytophthora cinnamomi with ohia decline on the Island of Hawaii. Phytopathology (in press).

Ohia seedlings transplanted to soil collected from declining forests became infected with Phytophthora cinnamomi and inoculations of healthy ohia trees in the field with soil and roots from declining forests resulted in root necrosis and P. cinnamomi was recovered. Phytophthora cinnamomi was recovered from 96% of the decline areas and from 24% of the apparently healthy areas sampled throughout the Island of Hawaii. Lupine baiting and the use of soil dilution plates indicated little difference population of the fungus in soil of declining and healthy forests. Addition of nutrients to ohia trees in the greenhouse had little effect on subsequent root infection by P. cinnamomi, and the fungus was recovered from soil in areas where declining ohia trees produced new growth following application of complete fertilizer. Fungicides reduced infection of ohia trees and lupine by P. cinnamomi in greenhouse and laboratory experiments. Broadcast applications of fungicides in addition to complete fertilizer to declining ohia trees resulted in a better response than application of complete fertilizer only.

4. Kliejunas, J. T., and W. H. Ko. Dispersal of Phytophthora cinnamomi on the Island of Hawaii. Phytopathology (in review).

Phytophthora cinnamomi was recovered by lupine baiting from soil particles carried on boots of humans, tires of vehicles, and hoofs of feral pigs. It existed in soil as chlamydospores and unknown propagules in organic matter. Zoospores of P. cinnamomi which were released when soil was submerged in water were dispersed by rain splash, or carried in runoff water. The fungus was trapped by lupine from streams and recovered from dead ohia leaves on the forest floor. It was isolated from the roots of 20 endemic, 2 indigenous, and 5 introduced plant species in 22 different plant families. All isolates tested were of the A^2 mating type.

F. RESEARCH UNDERWAY BUT NOT COMPLETED AT THE EXPIRATION OF THE GRANT.

1. Measurements of shoot growth on individual trees in 50 X 50 ft. plots in decline forests treated with complete fertilizer or NPK at rates of 100; and 300 lb./acre are being taken periodically. Growth after one year on fertilized versus control plots is presently being analyzed.

OVH
August 11, 1975

OZONE IN THE VALLEYS OF THE HIGH SIERRA NEVADA

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Abstract

Air quality affects the condition of forest vegetation. Damage to vegetation is due primarily to ozone and sulfur compounds. Atmospheric ozone values were recorded at three widely separated sites on the Sierra Nevada of California. The results suggest that ozone concentrations depend on three processes: (a) advection from air pollution sources, (b) downward transport from higher elevations because of mountain-wave turbulence, and (c) absorption-reemission processes in snowmelt water. Fluctuations in concentration have the spectral characteristics of a passive additive in a turbulent medium.

Introduction

What is the potential impact of various land-use plans on air quality in the Sierra Nevada of California? Damage to forest vegetation by airborne agents primarily is due to ozone and sulfur compounds. Therefore, current research is aimed primarily at defining the sources and concentrations of these gases. Sulfur compounds mainly occur near geothermal sources. They are usually localized insofar as origin and prediction is concerned. Ozone in mountainous areas presents a more difficult problem. The most apparent sources of ozone are photochemical reactions in the stratosphere and in polluted air from urban and other areas. Ozone is then advected into mountains by wind interactions with the terrain. High ozone values have been recorded in the Sierra Nevada when advection or photochemical reactions were either very weak or non-existent. These high values may be the result of the release of ozone dissolved into snow water.

This paper reports a study to determine the present state of air quality at selected areas in the Sierra Nevada of California and to define the meteorological and climatological conditions which are important in air quality.

Instrumentation

Ozone values were measured by a Dasibi Model 1003A ozone photometer[1]. This instrument is a self-contained unit, has a 70-cm long chamber and absorbs ultraviolet radiation (2537 A°). Air was sampled at a rate of 22 sec per sample at a flow rate of 2 l/m. Measured values are presented on a light emitting diode (LED) display. We also recorded this on an Esterline-Angus Series S strip chart recorder.* Response of the instrument was limited by the 22 sec cycle rate of the mechanical air pump sampling system. The intake of the Dasibi ozone monitor was placed at various levels (Table 1). Positioning was determined by local factors and weather conditions. The ozone photometer was calibrated by Robert Maxwell, Air Sanitation Engineer Associate, California Air Resources Board, with a secondary standard calibration ultraviolet photometer that is traceable to the primary standard ultraviolet photometer at the California Institute of Technology.

1/ Pacific Southwest Forest and Range Experiment Station, Berkeley, California, stationed at Riverside, California.
2/ California Region, San Francisco, California

* Trade names and commercial enterprises or products are mentioned solely for information. No endorsement by the U. S. Department of Agriculture is implied.

Concurrent observation of the temperature structure were recorded with a Mark VII acoustic echo sounder[2]. Winds and temperatures were recorded at 5 m and 15 m. The 5-m level was chosen because it was estimated to be the maximum snow level.

Study Sites

Observations of atmospheric ozone were made at three sites:

Kirkwood Meadows is a flat 330-m wide valley at 2300-m elevation near the eastern crest of the Sierra Nevada, 25 km south of Lake Tahoe. The northward drainage is between canyon walls 300 to 350 m high. The 2-km long valley drains into the American River, which runs east-west. It has heavy snows and frequent winter storms. The Kaweah River Valley is a complex river valley 29 km east of Visalia, California, which had four observation sites. Observations near the mouth of the canyon (elevation 150 m) where it enters the San Joaquin Valley at Lemon Cove were limited. The Hammond site at 365-m elevation, 21 km up the valley, was at the junction of the east and the main Fork of the Kaweah River. Oak Grove at 730-m elevation lies 5 km further eastward along the East Fork of the Kaweah River. The upper end of the East Fork valley (Farewell Canyon) is 37 km farther east of Oak Grove at 2300-m elevation. It is a "V-shaped" valley except for the upper 8 kms, which is a "U"-shaped glacial valley and runs north-south. The walls range from 500 to 1000 m high. This area is 30 km west of the Sierra Nevada crest, which is at 4200-m elevation.

Observations

Ozone was measured at the three sites during these weeks: Kirkwood Meadows, week of March 2, 1975; Farewell Canyon, weeks of February 23 and April 20, 1975. Snow depths varied (Table 1). Ozone was present about 35 percent of the time. Average concentrations varied from 0.03 to 0.15 ppm. Recent tests by the California Air Resources Board (ARB) indicate the values and our data should be reduced by 20 percent. Further, the data have not been reduced to sea level as recommended by the ARB since this practice is not universal.

Power spectral densities of the ozone concentrations from Kirkwood Meadows and Farewell Canyon were normalized by multiplying the frequency ordinate by the ratio of the observation height to the mean wind speed at that height. The power spectral density was normalized by multiplying the frequency and dividing by the variance of that data set (Fig. 1). The frequency of the Oak Grove measurements was not normalized because the wind speeds were less than the starting speed of the anemometer (0.025 m/sec (Fig.2)).

Discussion

Mesoscale (1- to 10-km) interactions between the mountains and the overall synoptic weather patterns produce eddy fluctuations in the wind which are dynamic and contain a good deal of energy. If ozone is a passive additive the normalized power spectral density curves should be close to a straight line when they are plotted on logarithmic paper. This is the case for the analysis (Fig. 1) of the daytime and storm experiments. There is little evidence of eddy dissipation (i.e., destruction) in these curves which would be

frequencies. The slow cycling time (20-22 sec) of the photometer limited the analysis of the higher frequency fluctuations.

The turbulent spectra from Oak Grove was displaced towards lower frequencies because of the light winds. Therefore, the photometer could respond to a portion of the decay spectra. Frequency, when plotted against power spectra density of the fluctuations shows a negative slope that resembles the -5/3rds slope described by Corrsen[3]. Our observations were recorded in rain during a storm as a "blob" of air swept up the valley over the measuring site. When the inversion disappeared, so did the ozone. This episode was probably associated with movement of polluted air from the San Joaquin Valley to the west. It shows that the turbulent microstructure of ozone in the atmosphere probably can be considered a turbulent passive additive, and that dissipation of ozone can be formulated as a turbulent phenomenon.

The largest values and the greatest fluctuations in ozone concentrations occurred between 0600 and 0800 PDT (Table 1). Values as great as 0.96 ppm were observed. The rapid fluctuations occurred each morning during clear weather before the sun's rays reached the valley floor. Since the winds were light and there was no temperature inversion, it seems unlikely that this ozone was advected by the wind from a remote source. These episodes occurred as temperatures fell below the freezing point of water. We believe that these high concentrations occurred as a result of the precipitation of ozone gas dissolved in the melt water surrounding the individual granules of the snowpack. This process is described as follows: Ozone is soluble in water at 0.49 cm^3 of ozone at standard pressure (1013.25 millibars) and zero degrees centigrade/cm^3 of solute. The snow density was 0.27 g/cm^3. It was 1.52 m deep and was 1 week old at the start of the experiment. No new snow fell until April 24. We did not detect any ice-lenses in the snowpack.

Snow quickly acquires a granular character after it has fallen. The snowpack density may range from 0.05 g/cm^3 for newly fallen snow to 0.5 g/cm^3 for an old snowpack. The snow particles range from 0.5 mm in diameter for new snow to 2 mm diameter for old snow. We estimated the particulate diameter to average 0.5 mm. If there are n snow particles per unit volume of snowpack and they have a mean radius $\bar{r}$, the snow density, ρ_s is the product of the density of the individual snow particle, ρ_i times the number of particles times the volume of each particle or,

$$\rho_s = \rho_i \, n \, \frac{4}{3} \pi (\bar{r})^3 \qquad (1)$$

We further assumed that the snow granules were covered with a layer of melt water of area A per unit volume as given by

$$A = 4\pi (\bar{r})^2 n \qquad (2)$$

Substitution for n in equation 2 into equation 1 gives

$$A = \frac{3}{(\bar{r})} \left(\frac{\rho_s}{\rho_i} \right) \qquad (3)$$

and snow and ice densities in Eq. (3) gives the effective surface to volume ratio as 3.2 cm^2 of surface to each cm^3 of volume. This snow could absorb about 3.2 times as much ozone as a flat water surface. This ratio compares favorably with the surface-reaction rate ratio between 24 hour old, 1 cm deep snow to that for a flat water surface reported by Aldaz[4].

Snow has a definite porous structure, and consequently, air moves into and out of it on a diurnal basis. This flow reaches depths up to 15 cm. We assume that an average effective depth is 7.5 cm, which provides an effective absorptive area 25 times greater than that for a flat water surface. A logical inference by freezing, snow ozone is released because it would no longer be held in solution. The rate of release should be a function of freezing of the snow water and diffusion rate of the ozone from the interior of the snowpack. We believe we observed this ozone release phenomenon at both high altitude sites; however, the upper Kaweah River Valley episode was the more dramatic. It occurred on clear mornings between 0600 and 0800 PDT from the time the snow cover froze until the time the sun's radiation reached the snow. Peak values as great as 0.96 ppm were observed on the LED display. These values exceeded the recorder's capabilities.

Conclusions

These observations suggest that ozone concentrations in the Sierra Nevada depend on three processes: (a) Advection from air pollution sources, (b) downward transport from higher elevation because of mountain-wave turbulence, and (c) absorption-reemission process in snowmelt water. Ozone damage to vegetation probably occurs as the end-product of a microphysical turbulence decay process, which can be explained by the conventional turbulence theory.

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le 1

Ozone values[1/] recorded by ozone photometer at three sites, Sierra Nevada, California, 1975

Site and elevation (m)	Date	Weather	Wind (m/sec)	Time (PDT)	Snow depth (m)	Sensor height (m)	Mean values (ppm)	Standard deviation (ppm)
Kirkwood Meadows (2300)	March 2	Snowing heavily	SW--5.6	1900 to 2100	2.41	2.4	0.112	0.015
Farewell Canyon (2300)	February 26	Clear	W--0.8	1200 to 1700	1.52	1.5	0.108	0.039
Farewell Canyon (2300)	April 22 April 24	Clear	Calm	0600 to 0800	2.44	1.5	0.135	2/
Oak Grove (700)	February 20	Rain	W. very light	1048 to 1208	None	0.3	0.076	0.043

1/ Uncorrected for altitude or more recent calibrations of instrument.
2/ Extreme fluctuations. Values to 0.960 ppm. Minimums 0.040.

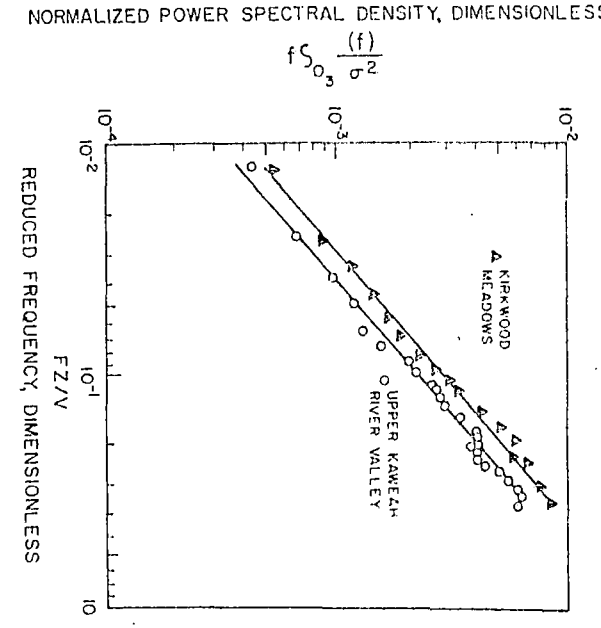

Figure 1--Power spectral density of the ozone fluctuations shows the observations from Kirkwood Meadows and Farewell Canyon probably had the same ozone source.

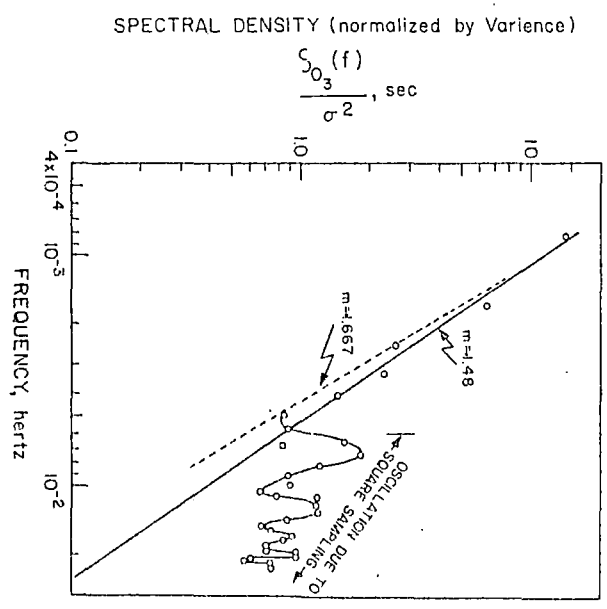

Figure 2--The spectrum of ozone fluctuations at Oak Grove on the East Fork of the Kaweah River shows an exponent form with a -5/3rds slope.